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by

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(Meteorological Office)

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## 1. Introduction

Strong westerly winds are a persistent feature in the upper troposphere over the Middle East in winter and early spring.

Detailed studies of the characteristics of jet streams in the neighbourhood of the British Isles have been made possible by the good distribution of R/S/W stations there. These studies have been supplemented by determination of profiles of individual jet streams over the British Isles by an aircraft photographic method as described by Hurst (1) (2).

Detailed studies of the characteristics of jet streams in the Middle East are hampered by the paucity of R/S/W stations in the region. Bannon (3), from an analysis of the upper air observations at Habbaniya and Bahrain for January, 1951, has constructed a meridional cross-section showing the mean structure for that month of the strong wind belt over Iraq and the Persian Gulf. Bannon's analysis is admittedly approximate, but it indicates that the strong wind belt is in the mean a broad stream without strong horizontal gradients. This suggests that there are considerable differences between the structures of jet streams in the Middle East and those experienced in the neighbourhood of the British Isles, a suggestion which is supported by day-to-day experience of high level charts in the Middle East.

Prior to the publication of Bannon's paper, plans were made for photographic sorties by aircraft based in the Middle East with the object of determining the profiles of individual jet streams using the flight technique and method of analysis described by Hurst. Sorties have been made in the winters of 1952-3, 1953-4, and 1954-5.

## 2. Method of analysis

Trial flights were made on December 5 and 7, 1952 by a Meteor X aircraft of No.13 Squadron between Habbaniya and Bahrain. The photographic prints were prepared at the Joint Air Photographic Intelligence Centre (Middle East), where the analysis was undertaken by Flight Lieutenant J.P. Wynton. It soon became evident that Hurst's method of analysis was not suitable for use in the Middle East because of the poor detail and small scale of the available maps.

Further sorties were flown between Port Said and Wadi Halfa on January 28 and February 6, 1953 and Wynton developed a new method of analysis, which has been used in determining all the profiles of jet streams discussed in this paper.

A vector wind scale was constructed for use with the prints, thus eliminating the need for accurate ground detail on maps. Briefly, the method is based on the fact that the principal point (P.P.) of a vertical aerial



/photograph

photograph indicates the aircraft's ground position (G.P.) at the time of exposure. Thus a strip mosaic of prints represents a series of G.P.'s of the aircraft, and the distance between any two adjacent P.P.'s divided by the camera time interval gives the ground speed to scale. If to the same scale and for the same time interval, the true airspeed is laid off vectorially on the aircraft's heading from the first P.P., the distance and bearing between the end of this vector and the second P.P. represent the wind distance to scale for the time involved, and also its direction.

Prints were plotted on a map to obtain terrain heights and total distance flown. The P.P. of each print was pricked with a fine point and transferred to the next print to become the transferred principal point (T.P.P.). At a later stage this process was simplified by having the P.P. engraved on the camera register glass.

The vector scale distance ("D" factor) was calculated using the formula

$$D = 42.9 \frac{VTF}{H} \text{ mm.}$$

where

V = True airspeed in knots
T = Camera operating time in seconds
F = Focal length of lens in inches
H = Height in feet of aircraft above the ground.

New values of the "D" factor were calculated whenever significant changes in V or H occurred. The "D" factor represents the true air distance to scale covered by the aircraft between the P.P.'s of two successive prints.

Each print was overlaid with the vector scale, positioned so that the T.P.P. was placed at the appropriate "D" factor distance for the print from the centre of the scale, with the vector base line parallel to the line of flight.

From the end of the vector base line (the centre of the scale) the distance and relative direction of the P.P. of the print were read by means of concentric 10 mm. rings and the bearing lines on the vector scale. This gave values of the wind vector distance (D') and relative wind bearing. The values of D' and relative wind bearing were averaged in groups of five prints and the final results determined from these averages to counteract fluctuations between individual print readings.

The wind vector distance D' was converted into wind speed by the formula

$$V^W = 0.02318 \frac{D'H}{T F} \text{ kt.}$$

The addition of the relative wind bearing to the true heading gave the wind direction.

The final stage in the analysis was the preparation of a histogram showing the variation of wind speed along the track, and a graph showing variation of wind direction. These pictorial representations of wind speed and direction are reproduced in this paper in respect of flights producing results of interest.

## 3. Accuracy of the method

There are several sources of error in the analyses, the results of which must be treated with some reserve.

In the formula $D = 42.9 \frac{VTF}{H}$ an error of 1% in either V, T, F or H will give rise to an error of approximately 0.5 mm. in D. As 0.5 mm. is the

maximum accuracy that can be expected from the scale measurement, an error of 1% is tolerable. Errors of 1% in T and F are unlikely, and may occur in V. The most suspect term is H, the height of the aircraft above the ground. Errors of more than 1% in H are likely over poorly mapped or hilly terrain.

Errors inherent in the formula $V^W = 0.02318 \frac{D'H}{T F}$ are likewise mainly small. An error of 1% in D will not produce any measurable change in D', but it may produce an error of approximately 2° to 5° in the relative bearing dependent upon the position of the vector scale and the distance from the P.P. Errors of 1% in H, T or F produce errors of less than 1.2% in the value of $V^W$. Thus $V^W$ is not likely to be appreciably disturbed by the normal errors to be expected in H, T or F.

Errors arise in handling the prints and vector scale. It is unlikely that physical errors of more than 0.5 mm. (which will produce an error of approximately 7 kt.) will occur in the readings along the vector scale base line, but in the readings of D' errors of up to 1 mm. must be allowed for. These errors partially cancel out in the mean groupings of five prints. An error of 0.5 mm. must be deemed possible in determining the position of the T.P.P. The position of the P.P. can be readily included on all prints by marking a dot on the camera register glass. This was done with the later sorties and eliminated the possibility of an error in marking the P.P., thus reducing the total possible error and making a considerable saving of time in marking the prints.

The vector scale method depends on maps for terrain heights and the overall distance of the run. As the majority of the runs were over comparatively subdued terrain, and differences in height up to 300 ft. in the final determination of the aircraft's effective height are negligible, map errors were reduced to a minimum.

The outstanding source of error can be attributed to the attitude of the aircraft. In addition to the normal yawing, pitching and rolling, several pilots experienced clear air turbulence during the runs. The effect upon the stability of the aircraft's flight is evident from the results. It is obvious that there is some connection between the variations in the results and the degree of turbulence. In general it can be assumed that the graphs fluctuate more where there is turbulence, and individual prints within these averages of five prints even more so.

Wynton estimates that with wind speeds in the region of 150 kt. results are correct to within 10 kt. and 10° to 12° of direction. The probable errors will be greater, of course, in regions of considerable turbulence.

## 4. Sorties and results

The nickname "Windy Run" was given to the project, and sorties are referred to for convenience by "Windy Run" numbers. This report covers Windy Run I to Windy Run XII.

### Windy Run I

Windy Run I consisted of two flights. The aircraft flew from Habbaniya to Bahrain on December 5, 1952, and returned to Habbaniya on December 7. These flights were largely exploratory and it subsequently proved impossible to make an accurate analysis.

### Windy Run II

Windy Run II was flown from Port Said to Wadi Halfa on January 28, 1953. The aircraft set course on a heading of 200° true, at a height of 38,000 ft., and at an airspeed of 380 kt. All these factors remained constant throughout the flight. An F.52 camera with a 14 inch focal length lens was used, and



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the camera time interval was 10 seconds. The camera failed after 61 minutes 40 seconds, when 370 exposures had been made.

The surface synoptic chart for 0300 G.M.T., January 28, 1953 is shown at Fig.1. Polar continental air covers southern Europe. Much of the air south of the polar front is of fairly recent polar origin in process of modification and there are considerable thermal gradients southwards to the typical Tropical continental air over south Arabia and the Sudan. The 1000 - 500 mb. thickness chart (not reproduced here) shows a tongue of cold air extending southwestwards to the central Mediterranean and Tunisia from a cold pool over Russia. Westsouthwesterly thermal winds of approximately 40 kt. prevail over Egypt.

The 200 mb. chart for 0300 G.M.T., January 28, 1953 is shown at Fig.2. The wide belt of strong winds that is usual for the winter season is displaced southwards in the region of the central Mediterranean. The observational data are quite insufficient to give details of the structure of the air-stream.

The winds found by the aircraft, using five-print means, are shown in Fig.3. The degree of scatter of the wind speeds and directions is to be expected in view of the possible errors inherent in the analysis. Ignoring the first wind value, which is abnormally low, winds were meaned over 25-print intervals (250 seconds, or approximately 22 nautical miles). Values are 104, 109, 123, 125, 115, 117, 123, 122, 129, 124, 125, 128, 138, 136, 138 kt.

Certain deductions can be made about the horizontal gradients of wind speed at 38,000 ft. from the aircraft winds and other observational data. The wind at Ankara at approximately 38,000 ft. was 270° 45 kt. and at Nicosia 260° 53 kt. This suggests that over a distance of approximately 300 nautical miles the horizontal gradient of wind speed is very small. Fig.3, despite the errors inherent in the analysis, indicates lighter winds over the northern half of the Canal Zone than elsewhere on the photographic run, and suggests that the region of increasing wind speeds at any given time as the jet stream is entered from the north overlaps the Canal Zone at the time of the flight. The accuracy of the analysis is such that the found wind maximum of 123 and 125 kt. in the third and fourth 25-print intervals cannot be regarded with certainty as a real maximum within the jet stream. It is sufficient to infer that there is a wide belt of strong winds from the third to the twelfth 25-print interval, i.e. over a distance of about 220 nautical miles, without any considerable gradients of wind speed in the horizontal. The winds show a little backing southwards, and the track of the aircraft is not exactly at right angles to the stream. Allowing for this, the width of this belt within the jet stream is about 200 nautical miles, and the mean wind speed 123 kt. The increase of wind speed between Nicosia and the cold edge of the wide belt of winds with little shear is 70 kt. in 280 nautical miles. Of course, the possibility of the existence of a wind maximum between Nicosia and the Canal Zone cannot be ruled out entirely, but no evidence is available to suggest that any such maximum did exist on this occasion. Johnson (4) gives mean velocity profiles at the levels of the centres of jet streams derived from cross-sections along lines of section from Greenland to the Mediterranean and from the Azores to the Baltic for January, 1950. The overall mean decrease of wind found by Johnson on the cold side of the jet is 95 kt. in 280 nautical miles, a value somewhat greater than that between Cyprus and the Canal Zone on this occasion. The increase of wind speed towards the end of the run is probably real, with wind speeds of the order of 135 - 140 kt. Even the five-print interval winds are remarkably constant, indicative of smooth flying conditions. This may be the real core of the jet. These maximum winds occurred over a range of more than 50 nautical miles. It is unfortunate that the camera failed at this crucial point.

/Hurst

Hurst (2), in his investigation of the jet stream over the British Isles on September 1, 1952 found a wind maximum of the order of 110 - 120 kt., which is not far short of the maximum winds found on Windy Run II. The maximum winds in the British Isles jet stream occurred over a distance of 40 nautical miles at most, with wind speeds on the cold side falling by 67 kt. in 75 nautical miles. This decrease was followed by a belt of winds of the order of 40 - 45 kt. over about 100 nautical miles. There was no wide belt of strong winds at or alongside the jet axis with little or no horizontal gradient of wind speed, such as occurred in the Middle East jet stream of January 28, 1953. Nor is there any evidence of wind decreases on the cold side of this Middle East jet stream of the order of 67 kt. in 75 nautical miles, though there may of course have been gradients over limited distances between the Canal Zone and Cyprus that were larger than the gradient of 70 kt. over the total distance of 280 nautical miles. The wide belt of light winds over Turkey is comparable with that found by Hurst over north Scotland in the jet stream of September 1, 1952.

Hurst (1), in his investigation of the jet stream over the British Isles on January 18, 1952, in which the maximum wind was 170 kt., found a decrease of wind strength of 90 kt. in 80 nautical miles on the cold side of the jet axis.

No deductions can be made on the structure of the warm side of this Middle East jet stream.

It is interesting to note that the Fayid pilot balloon ascent at 0800 G.M.T. on January 28 indicated a wind of 270° 115 kt. at 37,000 ft., the maximum height reached. This agrees remarkably well with Windy Run II.

Windy Run III

Windy Run III was flown from Port Said to Wadi Halfa on February 6, 1953. The aircraft set course from Port Said on a heading of 201° true at a height of 40,000 ft. and a true airspeed of 395 kt. In Windy Run II the F.52 camera fitted with a 14 inch lens resulted in large scale photographs which were not suitable for speedy analysis. On Windy Run III two cameras were used to obtain comparative results, an F.52 camera with a 20 inch lens and an F.24 camera with an 8 inch lens. The camera control setting was 10 seconds for the F.52 camera and 20 seconds for the F.24 camera. Photographs were taken over a distance of 310 nautical miles.

The surface synoptic chart for 0300 G.M.T., February 6, 1953 is shown at Fig.4. This is a typical winter situation in the region of the chart, with Polar continental air in the north and Tropical continental air in the south. The 1000 - 500 mb. thickness chart for that day (not reproduced here) shows a belt of maximum westerly thermal winds across the Mediterranean to south Iraq and the Persian Gulf.

The 200 mb. chart for 0300 G.M.T., February 6, 1953 is shown at Fig.5. This chart indicates a wide belt of very strong winds, and, despite the paucity of observations, suggests that the strongest winds occur near the north coast of Africa. The winds found by the aircraft, using five-print means, are shown in Fig.6. The increasing fluctuations in the results towards the end of the flight are indicative of clear air turbulence, which was particularly violent in the vicinity of Qena, near the end of the photographic run.

The results obtained by the two cameras agree well over much of the run. Wind speeds for the first 205 nautical miles were meaned over 15 prints with the F.24 camera and 30 prints with the F.52 camera (300 seconds, or approximately 30 nautical miles). The results are:-

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| F.24 | : 143 | 134 | 132 | 125 | 133 | 133 | 120 kt. |
| F.52 | : 141 | 132 | 133 | 131 | 134 | 132 | 135 kt. |

These figures suggest that over a distance of 205 nautical miles there is no appreciable gradient of wind speed in the horizontal. This result is similar to that found in Windy Run II. Wind directions fluctuate, but in general are between 275° and 290°, approximately at right angles to the track of the aircraft. The analysis does not locate the axis of the jet stream, but this was probably in the neighbourhood of Port Said. The wind found by the aircraft there, approximately 140 kt., is in agreement with the strongest winds reported by radar and pilot balloon at stations within the jet stream in early February.

The analysis is incomplete over the last 100 nautical miles of the flight, and the agreement between the cameras is not as good as earlier in the flight, but it appears that wind speeds are decreasing southwards in this region. The found wind speeds here are rather erratic and it is impossible to be dogmatic on the rate of wind decrease in the horizontal. However, it is probably not greater than 15-20 kt. over 100 nautical miles. Hurst found gradients of 20 kt. in 90 nautical miles and 72 kt. in 200 nautical miles on the warm sides of the jet streams of January 18 and September 1, 1952 respectively over the British Isles.

The analysis gives no information on the decrease of winds on the cold side of the jet stream. The found wind speeds over the north of the Suez Canal Zone are of the order of 135 - 140 kt. The radar wind at 40,000 ft. at Nicosia on the same morning was 72 kt. This represents a decrease of wind speed of approximately 65 kt. in 250 nautical miles on the cold side of the jet stream. Hurst found gradients of 90 kt. in 80 nautical miles and 67 kt. in 75 nautical miles on the cold sides of the jet streams of January 18 and September 1, 1952 respectively. It cannot be deduced from these figures that the decrease of wind speed on the cold side of this Middle East jet stream is considerably less than those of the British Isles jet streams, for the very strong winds over the Canal Zone may have persisted with but little change of speed for some distance north of the Canal Zone.

On February 2, 1953, in the westerly airstream, winds were appreciably below 100 kt. at all levels at Malta, Benina, Nicosia, Fayid and Habbaniya, whilst at Bahrain winds of 116 and 129 kt. were reported at 200 mb. in the morning and afternoon respectively. Wind increases at Nicosia, Habbaniya and Fayid during the next few days were associated with the arrival of colder air on the northern side of the westerly airstream. The 1000 - 200 mb. thickness at Nicosia fell 710 ft. between the 2nd and 4th, and high level winds of over 100 kt. were reported there on the 4th and 5th. The 1000 - 200 mb. thickness at Habbaniya fell 1030 ft. between 3rd and 7th, and high level winds of over 100 kt. were reported there on 4th, 5th and 6th. Cairo reported a wind of 117 kt. and Fayid 140 kt. at 40,000 ft. on the afternoon of the 4th. Thickness changes at Bahrain were more erratic, and between 3rd and 7th there was a fall of 120 ft. The 200 mb. winds at Bahrain oscillated around 100 kt. throughout this period. A small veer of wind travelled eastwards in the airstream during the period, moving across Malta on the night of 3rd - 4th, Nicosia on the night of 5th - 6th, and Habbaniya on the night of 6th - 7th.

Windy Run IV

Windy Run IV was flown from Habbaniya to Bahrain on March 14, 1953. The camera failed after 32 minutes, and no results of value were obtained from the analysis.

Windy Runs V and VI

These sorties from the Canal Zone to Wadi Halfa and return on January 5, 1954 were abortive due to camera failures.

/Windy

Windy Run VII

Windy Run VII was flown on January 2, 1954 from Kabrit in the Suez Canal Zone to Wadi Halfa. A course of 195° true was maintained throughout the flight. The first 90 photographs were taken during climb from 30,000 to 40,000 ft., the next 82 at 40,000 ft., and the final 55 during descent to 30,000 ft. The camera time interval was 15 seconds, therefore photography at level flight at 40,000 ft. was limited to about 20 minutes, or over a distance of approximately 120 nautical miles.

The 200 mb. chart for that day indicates the usual strong westsouthwesterly airstream over Egypt. The five-print wind speeds for the section flown at 40,000 ft. show the fluctuations typical of these analyses. Apart from a possible slight decrease of wind speed southwards there is no discernible wind change of note over the distance (approximately 120 nautical miles), and the analysis adds nothing new to the results obtained by Windy Runs II and III.

Windy Run VIII

Windy Run VIII was flown from Habbaniya to Bahrain on January 16, 1954. The actual photographic run was made from Hilla to Kuwait. The aircraft set course on 139° true, which was changed to 152° true after nine minutes. The now standard F.24 camera with an 8 inch lens was used. The first 50 exposures were taken during climb from 30,000 to 40,000 ft., and 110 exposures were taken at 40,000 ft., when the camera failed. The camera time interval was 11.2 seconds, and the photographic run covered 240 nautical miles.

The surface synoptic chart for 0300 G.M.T., January 16, 1954 is shown at Fig.7. Polar air masses, with no well-defined fronts, prevailed over most of the area. The 1000 - 500 mb. thickness chart (not reproduced here) shows a belt of strong westsouthwesterly or southwesterly thermal winds over much of Egypt, southern Iraq and northern Saudi Arabia.

The 200 mb. chart for 0300 G.M.T., January 16, 1954 is shown at Fig.8 and indicates a very strong flow over Iraq.

The winds found by the aircraft are shown in Fig.9. Winds found during the climb (print numbers 1 to 50) are of no value in determining the profile of the jet stream. The scatter of the results at this stage of the run is undoubtedly influenced by turbulence which was reported at the beginning of the flight. During level flight at 40,000 ft., and for a distance of about 110 nautical miles, Fig.9 indicates a west wind of approximately 155 - 165 kt. Towards the end of the run Fig.9 indicates decreasing wind speeds followed by an increase but the results must be treated with reserve at this stage of the run, for turbulence was experienced here as well as at the beginning of the run. The track of the aircraft was not at right angles to the wind direction. Allowing for this, the width of the belt within the jet stream wherein there is but little gradient of wind speed in the horizontal is about 75 nautical miles.

An attempt was made to estimate horizontal wind gradients over greater distances within the jet stream, but these estimates must be treated with reserve in the absence of precise information on the exact position and intensity of the jet axis. Over a period of several days around January 16, 1954 the strongest winds reported by Habbaniya around 40,000 ft. occurred on January 16. On that date the Habbaniya winds at 40,000 ft. were 257° 177 kt. and 265° 174 kt. at 0300 and 1500 G.M.T. respectively. The axis of the jet stream was probably very near Habbaniya, but it is possible that the wind at the axis was somewhat stronger than the winds reported by Habbaniya. The aircraft began its run at 40,000 ft. approximately 110 nautical miles to the south of Habbaniya, and 75 nautical miles farther south the wind reported by the aircraft was approximately 155 kt. This gives a minimum value for the decrease of wind speed on the warm side of the jet axis of approximately 20 kt.

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in 185 nautical miles. Bahrain reported radar winds of 270° 94 kt. and 270° 82 kt. at 200 mb. (approximately 40,000 ft.) at 0300 and 1500 G.M.T. respectively. This indicates a decrease of wind speed of the order of 67 kt. in a north-south distance of approximately 250 nautical miles between the head of the Persian Gulf and Bahrain. Between the latitudes of Habbaniya and Bahrain the decrease is 87 kt. in 435 nautical miles.

On the cold side of the jet stream the wind at 200 mb. decreased by 155 kt. in a south-north distance of 275 nautical miles (wind 180 kt. at Habbaniya and 25 kt. at Diyarbakir in Turkey).

The mean velocity profiles at the levels of the centres of jet streams found by Johnson (4) give a mean decrease on the warm side of 90 kt. in 435 nautical miles, in close agreement with the decrease between Habbaniya and Bahrain on this occasion. On the other hand, the decrease to the north of Habbaniya on this occasion, 155 kt. in 275 nautical miles, is considerably greater than the mean decrease found by Johnson on the cold side of the Atlantic jet streams, 95 kt. in 275 nautical miles. Horizontal wind gradients in these Middle East westerly jet streams have been estimated from observed winds at stations not in the same longitude, but the available wind data over a period suggest that this is unlikely to introduce any appreciable errors in the estimated gradients at right angles to the jet stream.

Windy Run IX

Windy Run IX was flown on February 25, 1954 from Habbaniya to Bahrain. The photographic run was started north of Habbaniya and ended over Kuwait. The height was 37,000 ft., the heading 170° true and airspeed 383 kt. A F.24 camera with 8 inch lens was used, with control setting 15 seconds. The camera cut out after 52 minutes, having made 208 exposures over a ground distance of 375 nautical miles.

The surface synoptic chart for 0300 G.M.T., February 25, 1954 is shown at Fig. 10. This was the aftermath of a typical synoptic sequence in the Middle East, in which a complex low pressure system moved eastwards from the central Mediterranean and across Iraq. In the extreme north of the chart area the air is Polar continental, with greatly modified Polar air over much of the rest of the area. The 1000 - 500 mb. thickness chart for that date (not reproduced here) shows a belt of strong westsouthwesterly thermal winds over Egypt, Iraq and northern Saudi Arabia.

The 200 mb. chart for 0300 G.M.T., February 25, 1954 is shown at Fig.11. The winds found by the aircraft are shown at Fig.12.

The wind speeds are rather erratic over the first thirteen five-print intervals, varying between 157 and 186 kt., with a mean of 169 kt. Over the next thirteen five-print intervals the wind speeds are in general remarkably steady, with a mean of 169 kt. These represent a distance of about 230 nautical miles over which there was a belt of strong winds with no pronounced trends in wind speed that could be detected by this photographic method. The wind direction was just south of west, and allowing for the fact that the track of the aircraft was not at right angles to the wind, this belt within the jet stream was about 210 nautical miles wide.

Ignoring the final five-print wind, which is abnormally low, Fig.12 indicates a gradual decrease of wind speed of the order of 20 kt. in the final north-south distance of 135 nautical miles. Bahrain reported a wind of 85 kt. at 37,000 ft., representing a decrease southwards from Kuwait to Bahrain of 65 kt. in 175 nautical miles. Over the entire distance of decreasing winds there is a decrease of 85 kt. in 310 nautical miles. Johnson (4) found a mean wind decrease of about 70 kt. over this distance on the warm side of Atlantic jet streams. The increasing shear southwards from the centre of the jet stream agrees with the mean shear profile found by Johnson over comparable distances.



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The winds found by the aircraft in the neighbourhood of Habbaniya at 37,000 ft. were 265 - 270°, 169 kt. at 0930 G.M.T. The maximum winds reported by Habbaniya were 264° 150 kt. at 36,200 ft. and 263° 159 kt. at 36,200 ft. at 0200 and 1400 G.M.T. respectively.

Windy Run X

Windy Run X was flown on the morning of February 26, 1954 from Bahrain to Habbaniya. The height was 37,000 ft., the heading 310° true, and airspeed 390 - 395 kt. Unfortunately the camera failed after 31 minutes, 124 exposures having been made covering a ground distance of 169 nautical miles.

The surface synoptic chart for 0300 G.M.T., February 26, 1954 shows little change from that on the 25th, but the depression over Turkey had deepened somewhat, and an associated trough of low pressure was developing southeastwards towards the Persian Gulf. The 200 mb. chart shows falling heights at Nicosia and Habbaniya.

The winds found by the aircraft are shown at Fig.13. Increasing turbulence was experienced northwards on this flight, varying from slight to moderate, and this is reflected in greater fluctuations of found wind speeds in the north.

Found wind speeds increased northwards. The mean wind speed over the first five five-print intervals is 121 kt., and 145 kt. over the last five five-print intervals, giving an increase of 24 kt. in a distance of about 130 nautical miles at right angles to the wind flow. It is interesting to note that this wind change is less than that deduced from Windy Run IX on the previous day for the region Kuwait - Bahrain. This agrees with the mean shear profile published by Johnson (4), which shows decreasing shear at considerable distances from the centre of the jet.

The aircraft started its photographic run to the south of Bahrain, and in the latitude of Bahrain the found wind was 260° 130 kt. This agrees well with the radar wind at Bahrain on that morning, namely 260° 138 kt. at 250 mb.

Windy Run XI

Windy Run XI was flown on the morning of March 5, 1955 from the Canal Zone to Wadi Halfa. The height was 35,000 ft., the heading 194° true, and airspeed 390 kt. The standard 8 inch camera was used, and 176 exposures were taken between Port Said and 27°N, a distance of 255 nautical miles.

The surface synoptic chart for 0300 G.M.T., March 5, 1955 is shown at Fig.14. This was the aftermath of a typical synoptic sequence in which a complex secondary depression and associated cold front moved eastwards across the eastern Mediterranean and Turkey to Iraq and the Persian Gulf. The 1000 - 500 mb. thickness chart (not reproduced here) shows westsouthwesterly thermal winds of the order of 40 - 50 kt. over the eastern Mediterranean and northeast Egypt.

The 300 mb. chart for 0300 G.M.T. March 5, 1955 is shown at Fig.15 and the winds found by the aircraft are shown at Fig.16.

The first reported wind direction, 295°, is probably wrong. Over the five-print intervals two to thirteen the wind direction is 250 - 270°, and the mean wind speed 55 kt. There is a suggestion of a slight increase of speed southwards, the average over the five-print intervals nine to thirteen being 58 kt. Therefore over the first 94 nautical miles the winds averaged 250 - 270° 55 kt., with a possible small increase of speed southwards.

The fourteenth and fifteenth five-print intervals indicate a sharp veer of wind, with only a small increase of speed, namely 313° 68 kt. and 288° 62 kt.

/These

These are followed by a rapid increase of wind speed over the five-print intervals 16 to 20 (no value is available for 18). The mean wind direction over five-print intervals 14 to 20 is 310°. The strong wind, with mean direction 318°, is maintained to the end of the photographic run with the usual fluctuations of speed typical of the analysis, and with no discernible trend. The mean speeds for five-print intervals 20 - 24, 25 - 29 and 30 - 35 are 136, 142 and 138 kt. respectively. Accepting a wind speed of 65 kt. for interval 14 (the mean of 14 and 15) and 136 kt. for interval 20 (143 kt. was reported for interval 20, and indicates that the wide belt of strong winds in the south was reached in interval 20), there was a wind increase of 71 kt. in 44 nautical miles along the track of the aircraft, or in 36 nautical miles at right angles to the wind direction. This shear is greater than any observed by Hurst on the cold side of U.K. jet streams, but in Hurst's examples there were no troughs as possible complicating factors. It is interesting to note, however, that there was little or no wind shear in the WSW - W winds on the eastern side of the trough. The belt of strong winds (318°, 139 kt. approximately) persisted for 117 nautical miles along the track of the aircraft, or approximately 85 nautical miles at right angles to the wind direction.

During the first days of March, 1955 a complex secondary depression and associated cold front moved eastwards across the eastern Mediterranean and Turkey to Iraq and the Persian Gulf. At the beginning of the period there was a well-defined trough at 300 and 200 mb. lying north-south at approximately 10°E over the Mediterranean and north Africa, and a wedge at approximately 35°E. Although the wedge moved eastwards and high level winds veered in the central Mediterranean the eastward moving cold front was not immediately followed by a well-defined trough.

On the morning of March 5 the 300 mb. chart as drawn at No.1. (ME) Met. Unit (see Fig.15) suggests some degree of troughing over northeast Africa in addition to the well-defined trough over Greece and the central Mediterranean, but observational data are quite insufficient to permit any degree of confidence in the chart over northeast Africa. Similar arguments apply to the 200 mb. chart (not reproduced here). There is no evidence to suggest a northwesterly wind at 35,000 ft. just south of the Canal Zone.

The radar winds reported by Nicosia on March 5, 1955 at 35,000 ft. were approximately 240° 80 kt., and coupled with the winds found by the aircraft over the Canal Zone indicate a wind maximum to the north of the Canal Zone in the westsouthwesterly air stream. This is verified by winds reported at approximately 30,000 ft. on that day:-

| | | | | |
|---|---|---|---|---|
| Nicosia | : | 0300 G.M.T. | 250° | 78 kt. |
| Nicosia | : | 1500 G.M.T. | 240° | 88 kt. |
| Fayid | : | 0900 G.M.T. | 250° | 72 kt. |
| Cairo | : | 1500 G.M.T. | 250° | 63 kt. |

It is unfortunate that neither Fayid nor Cairo reported winds at levels as high as 35,000 ft. on that day.

The aircraft experienced the wind veer some 25 nautical miles south of the latitude of Cairo at approximately 0745 G.M.T., and just east of the position of the Cairo balloon at 30,000 ft. on that afternoon. There are no reported winds for levels as high as 35,000 ft. over Egypt during the days immediately following March 5, but the 300 mb. chart for 0300 G.M.T., March 6, despite the paucity of information, does suggest a well-defined trough extending from just west of Cyprus southsoutheastwards along the Red Sea. Subsequent charts verified the existence of this trough, and by March 8 there was a well-defined wedge over the eastern Mediterranean and Egypt, with the trough over Iraq and Saudi Arabia.

/Windy

Windy Run XII

Windy Run XII, flown from the Canal Zone to Wadi Halfa on May 17, 1955, was abortive on account of camera trouble.

## 5. Conclusions

The strong westerly winds over the Middle East in winter, at heights approximating to those of maximum wind speeds, contain a belt of very strong winds which may be as wide as 200 nautical miles or more, and in which horizontal gradients of wind speed are small or negligible. The method used to study the jet profile is not sufficiently accurate to determine the number, distribution and intensity of any wind maxima that may occur within these belts. The horizontal wind shear on the warm and cold side of these central belts of very strong winds appears to be of the same order as that found in jet streams over the northeast Atlantic and western Europe.

An interesting example of very strong wind shear was found in the northwesterlies just behind a trough at 35,000 ft., and on the cold side of the belt of very strong winds. There was no perceptible clear air turbulence in the region of strong shear.

## 6. Acknowledgements

I express my thanks to Flight Lieutenant Wynton whose method of analysis and production of results involved him in a lot of work additional to his normal duties. The co-operation of No. 13 Squadron, Royal Air Force is also much appreciated.

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(1) Hurst, G.W. 1952 Air Ministry, London, Meteorological Research Papers, No. 722.

(2) Hurst, G.W. 1952 Air Ministry, London, Meteorological Research Papers, No. 772.

(3) Bannon, J.K. 1953 Air Ministry, London, Meteorological Research Papers, No. 821.

(4) Johnson, D.H. 1952 Air Ministry, London, Meteorological Research Papers, No. 761.

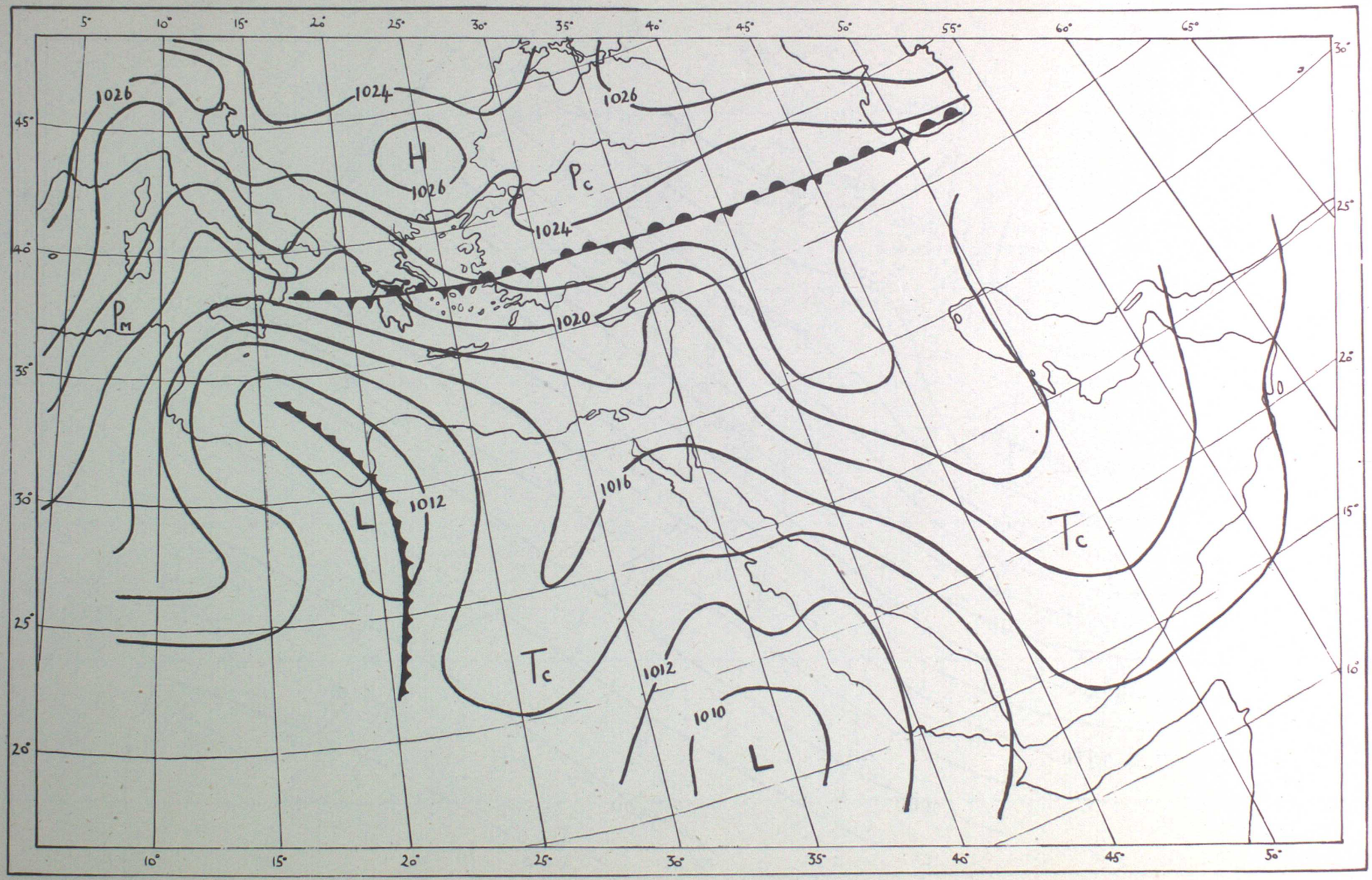


Fig. 1. Surface Synoptic Chart. 0300 G.M.T. January 28, 1953

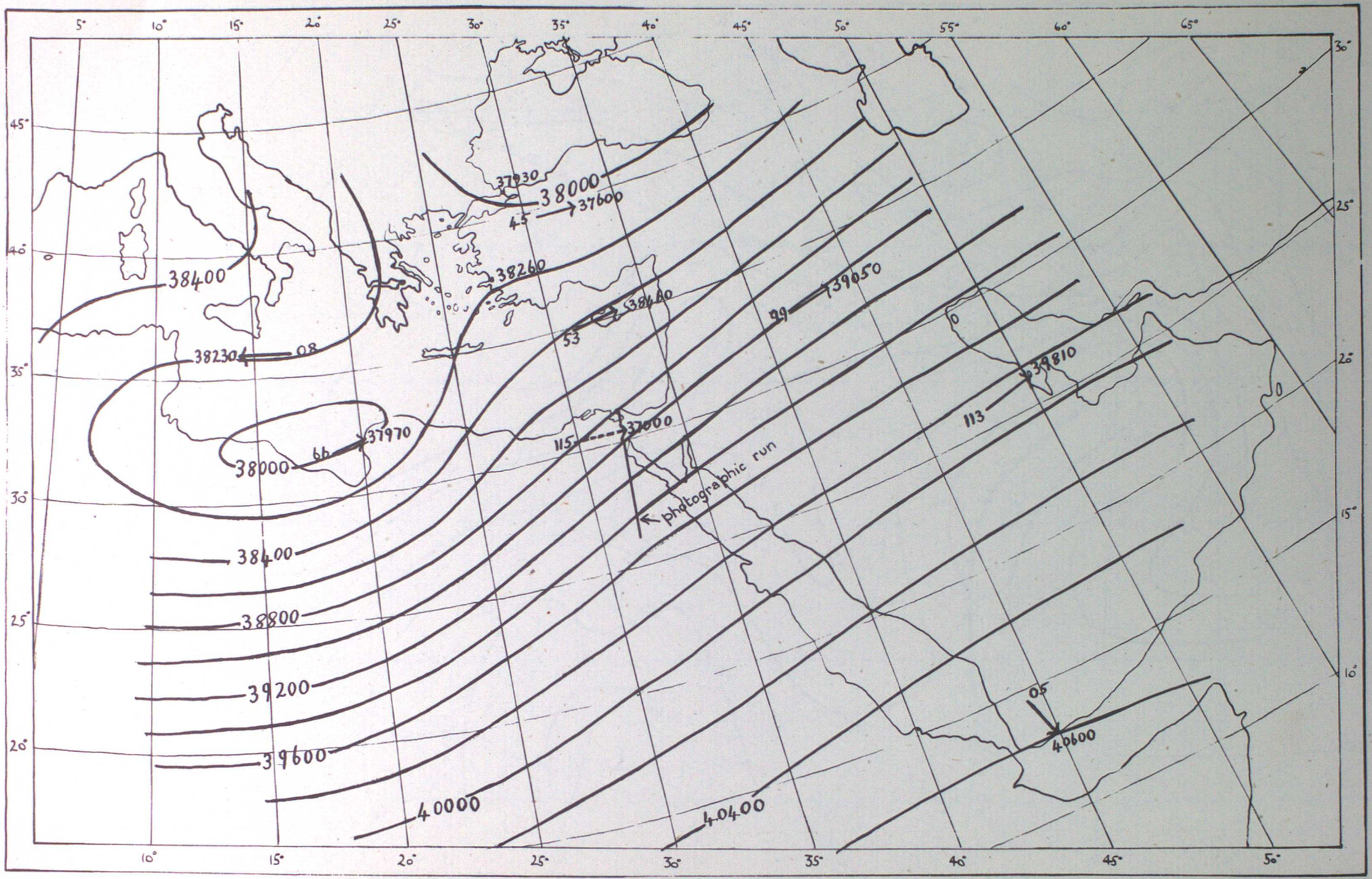


Fig. 2. 200mb. chart 0300 G.M.T. January 28, 1953. 200mb. heights (feet) and radar winds (knots) 100 ⟶ 38,500
Pilot balloon wind (knots) at heights indicated 60 - - → 35,000

M.R.P. 932

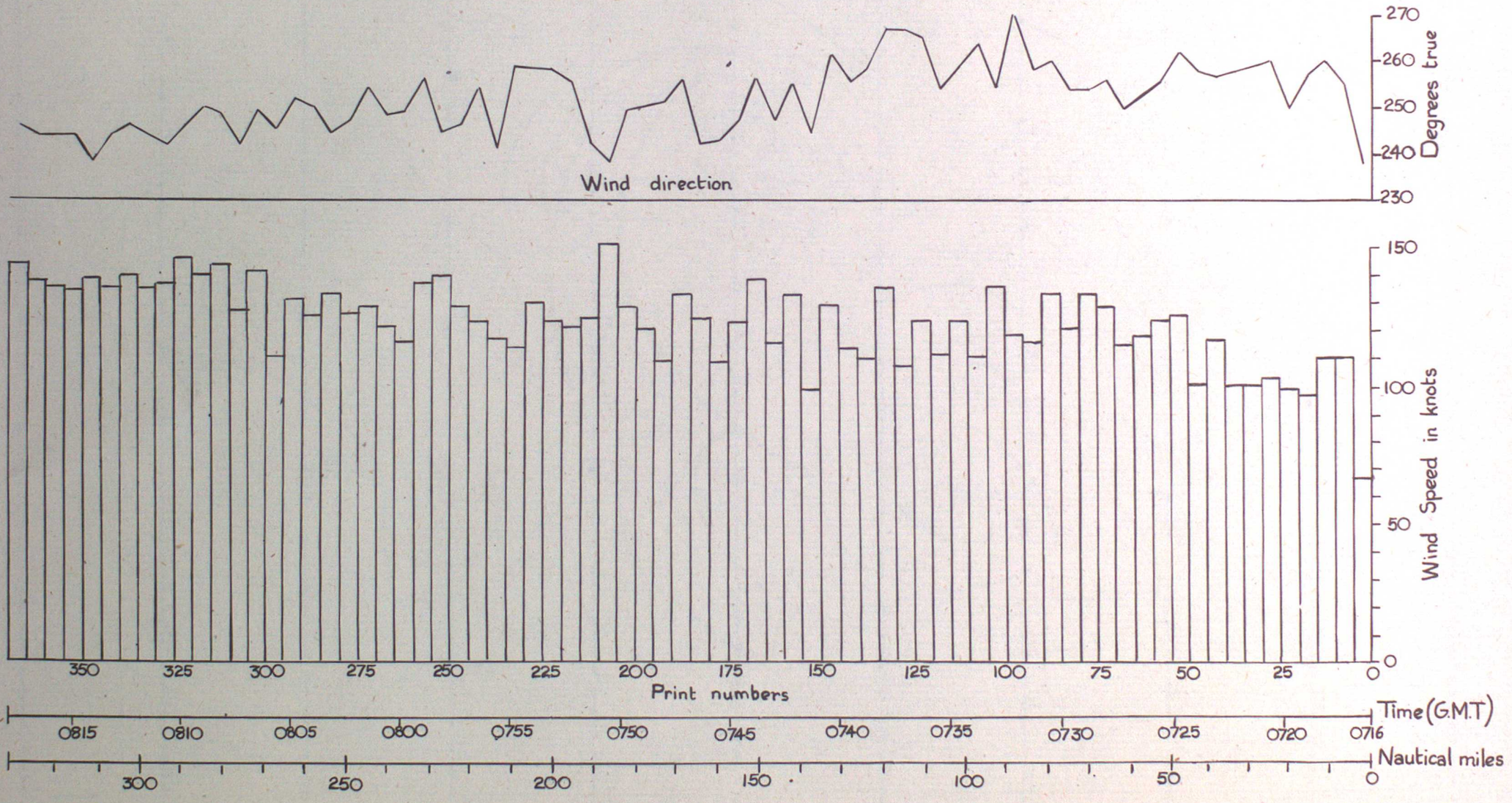


FIG. 3. Windy Run II January 28, 1953.

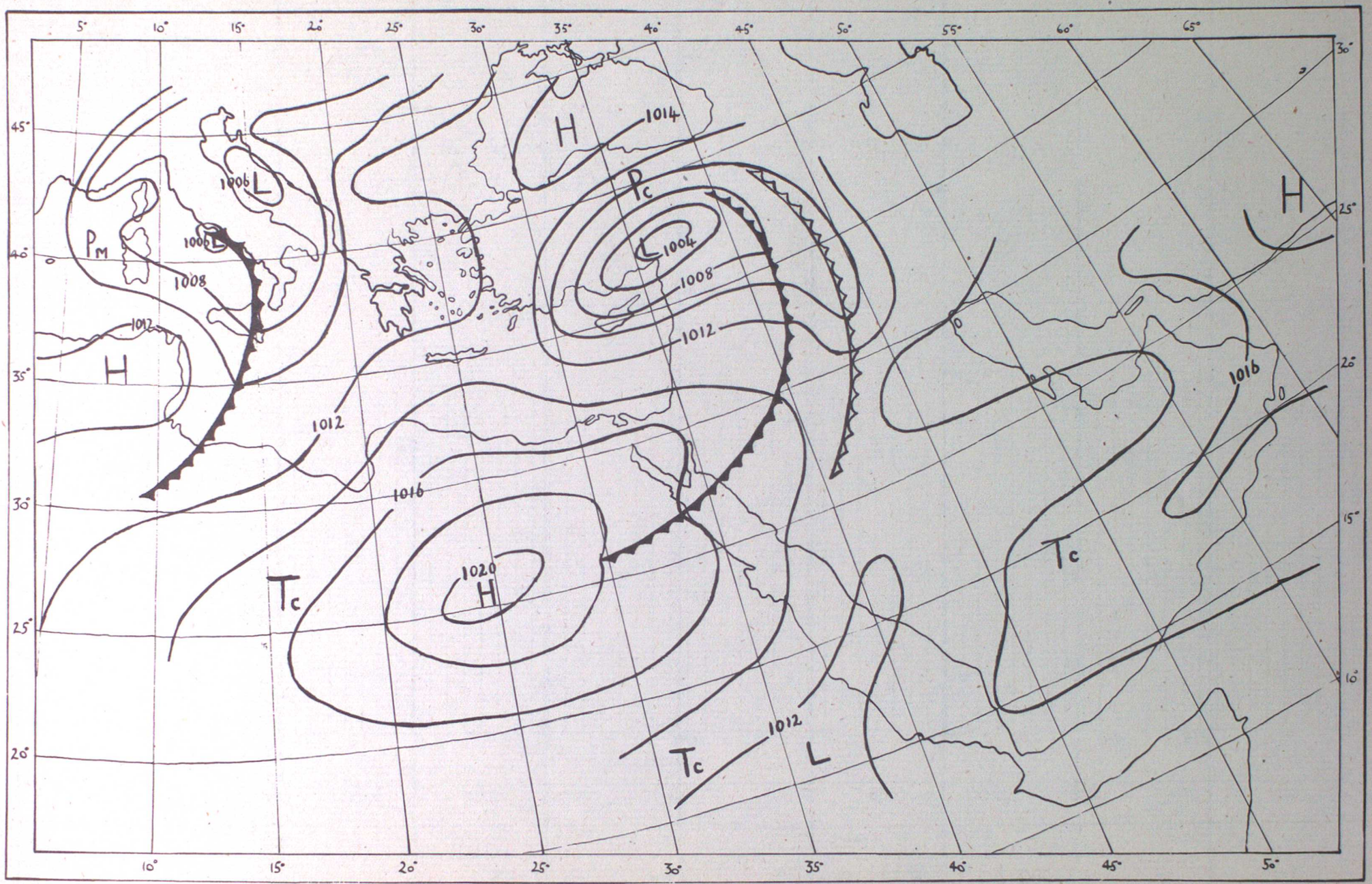


Fig. 4. Surface Synoptic Chart 0300 G.M.T. February 6, 1953.

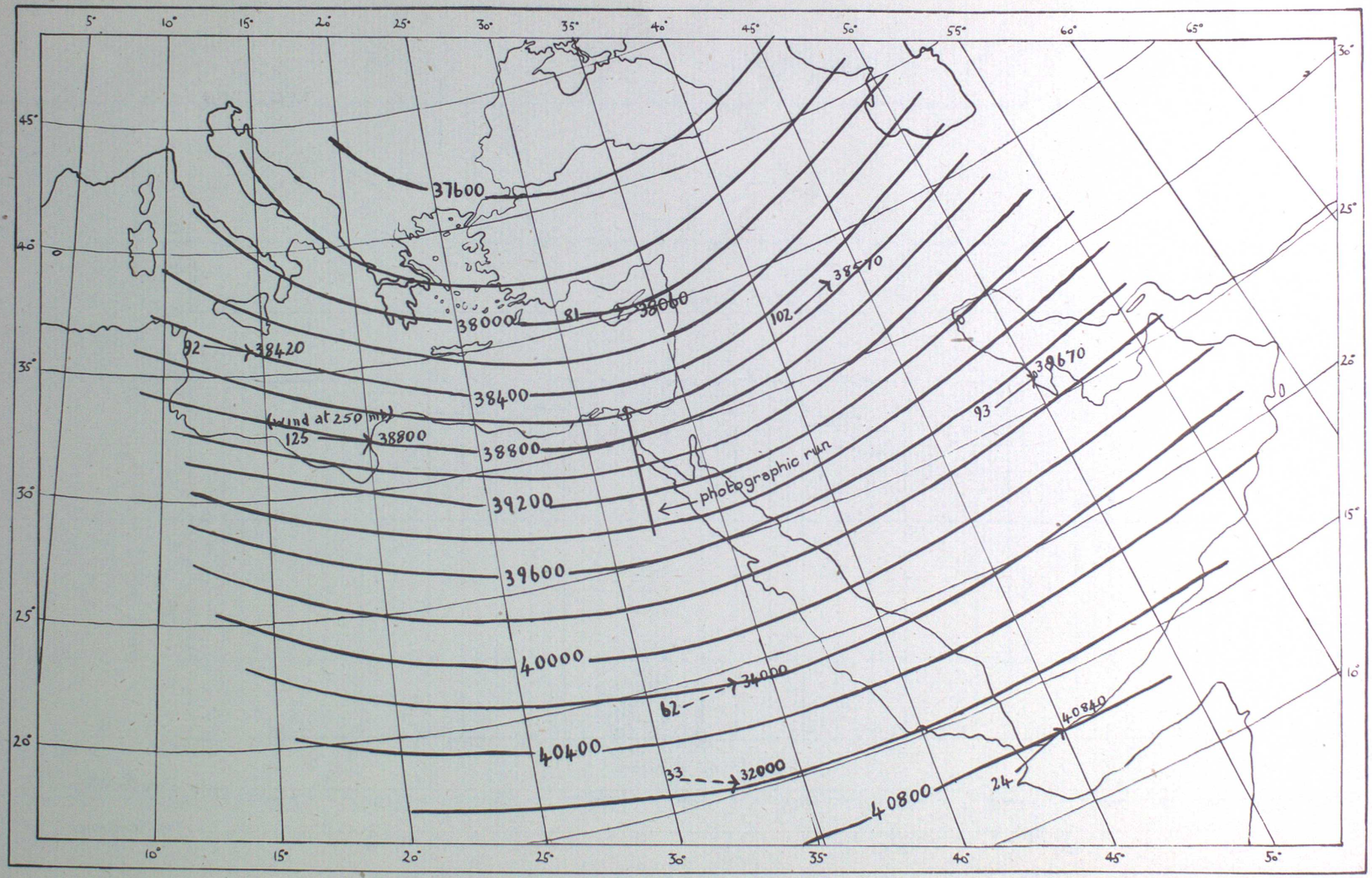


Fig. 5. 200 mb. chart. 0300 G.M.T. February 6, 1953.

200 mb heights (feet) and radar winds (knots) 100 ⟶ 38,500
Pilot balloon winds (knots) at heights indicated 60 - - → 35.000

M.R.P. 932

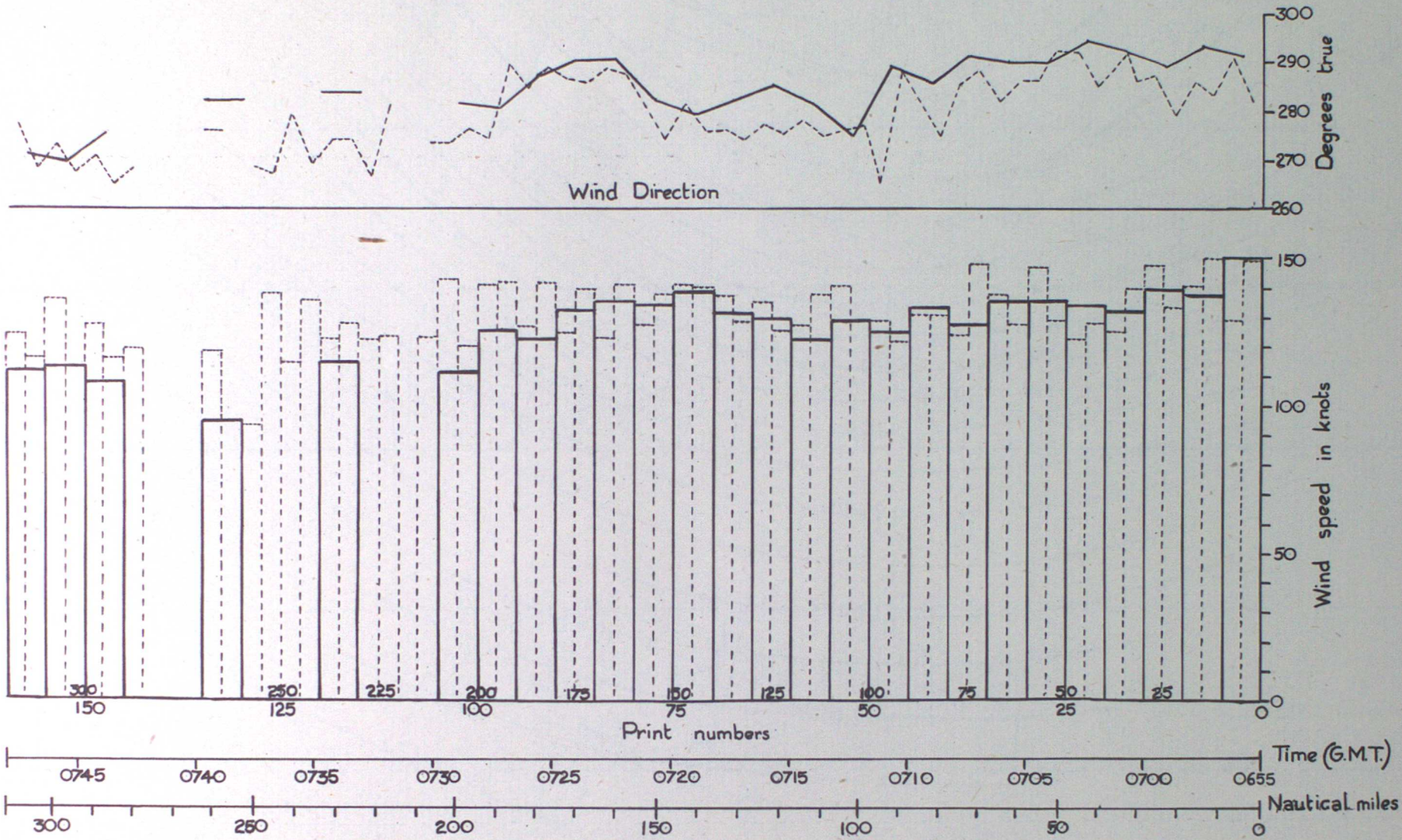


FIG. 6. Windy Run III February 6, 1953. ——— F 24 camera ----- F 52 camera

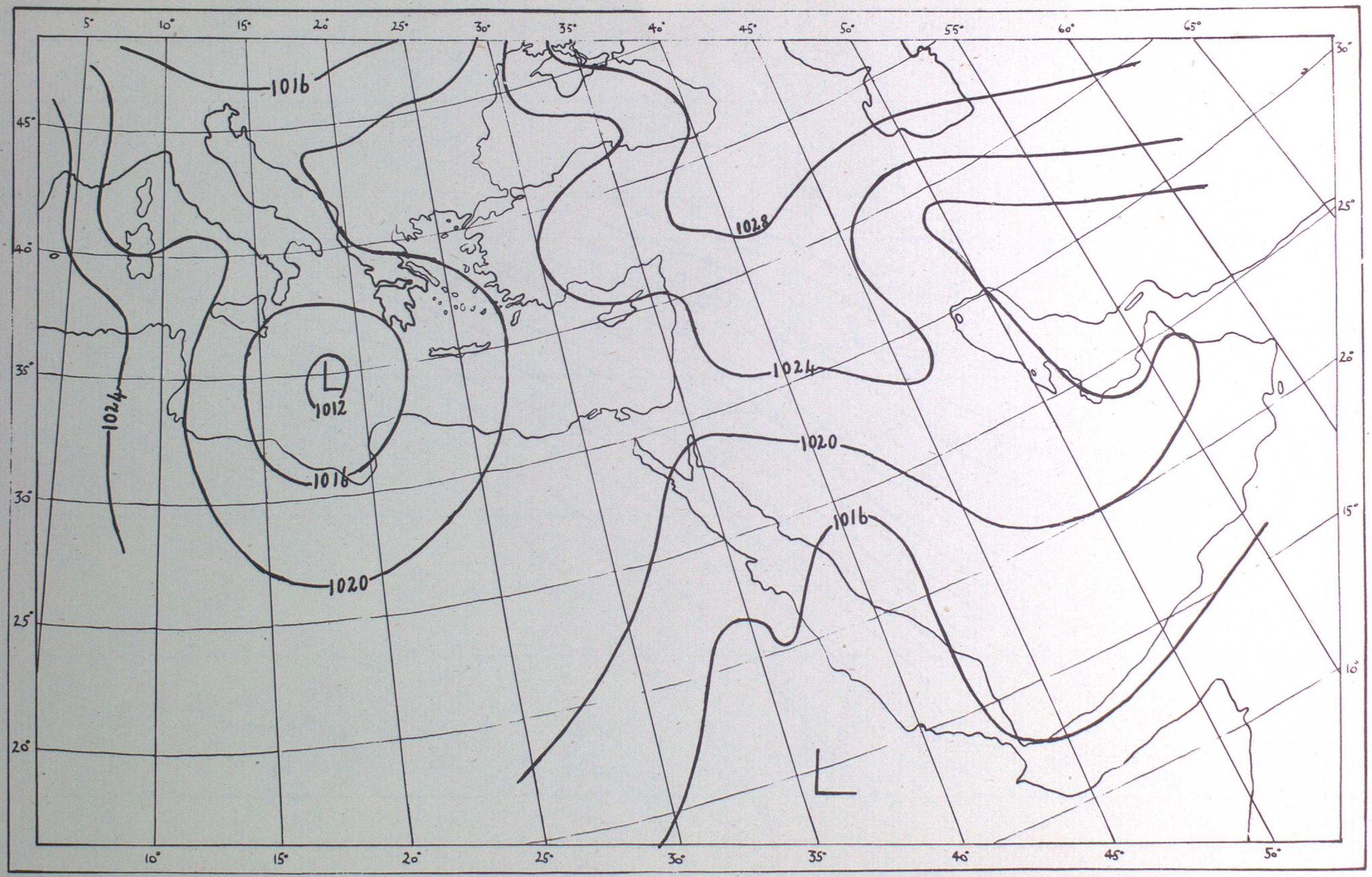


Fig. 7. Surface Synoptic Chart. 0300 G.M.T. January 16, 1954.

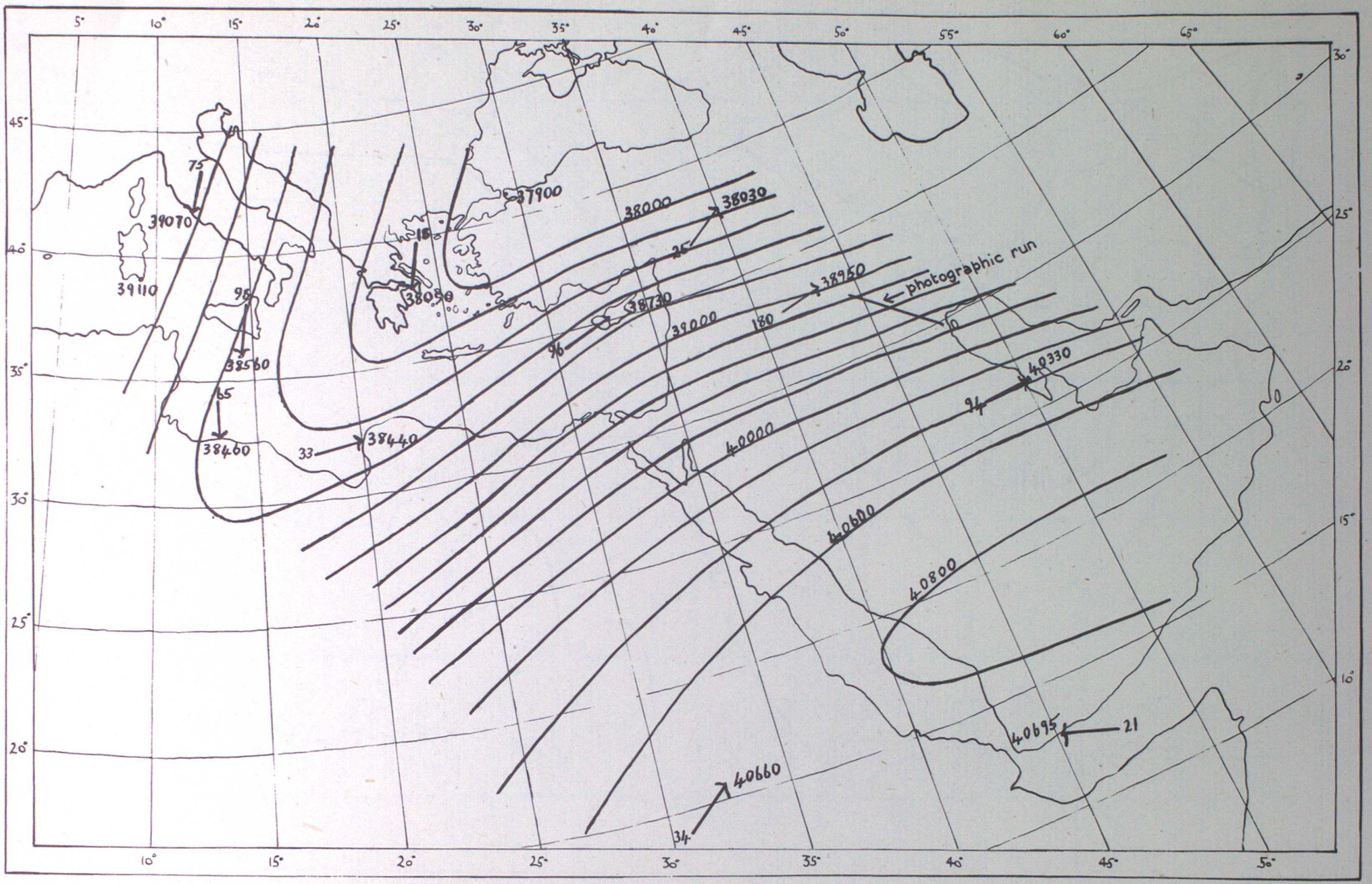


Fig. 8. 200 mb. chart. 0300 G.M.T. January 16, 1954. 200 mb. heights (feet) and radar winds (knots) 100 ⟶ 38,500

M.R.P. 932

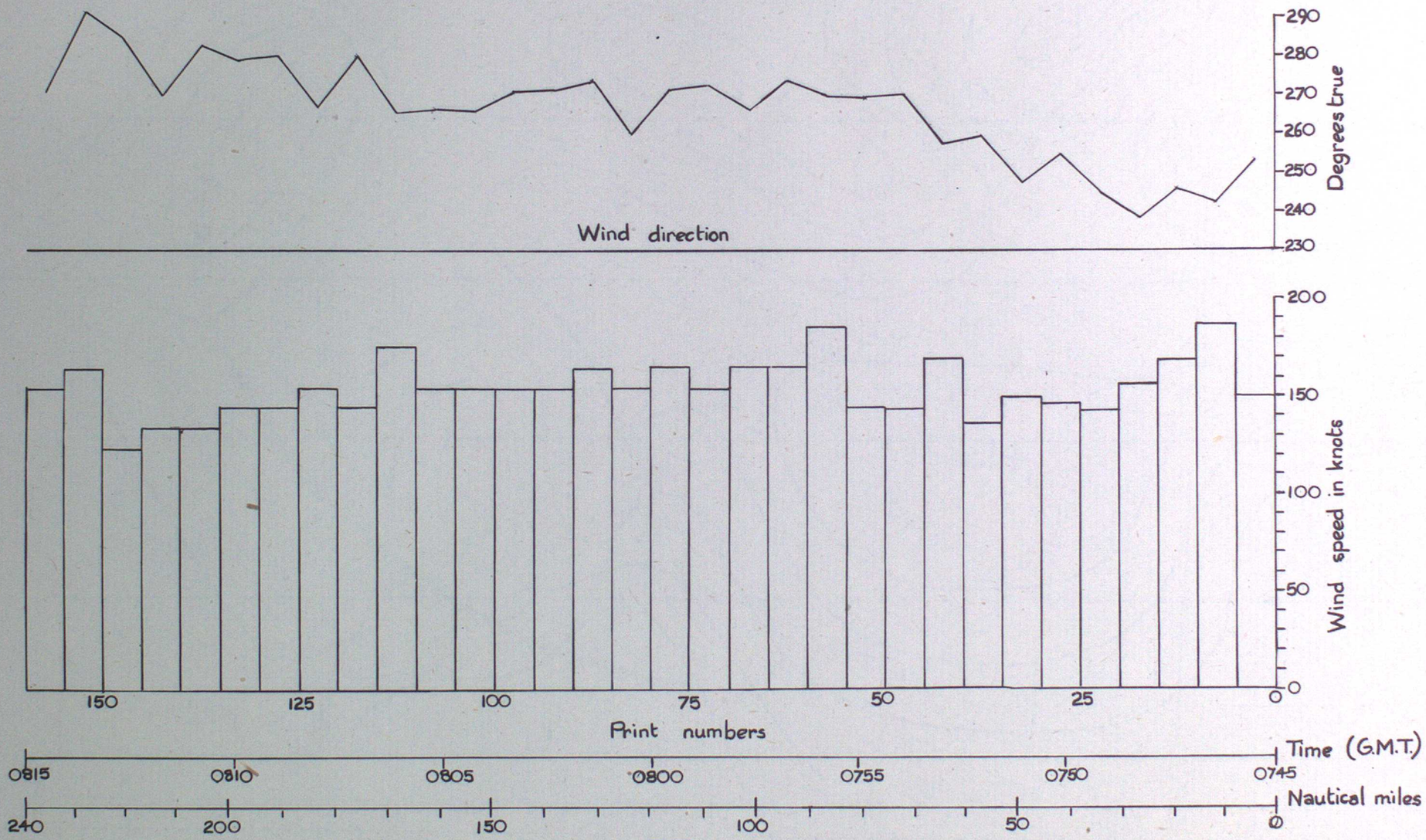


FIG. 9. Windy Run VIII January 16, 1954.

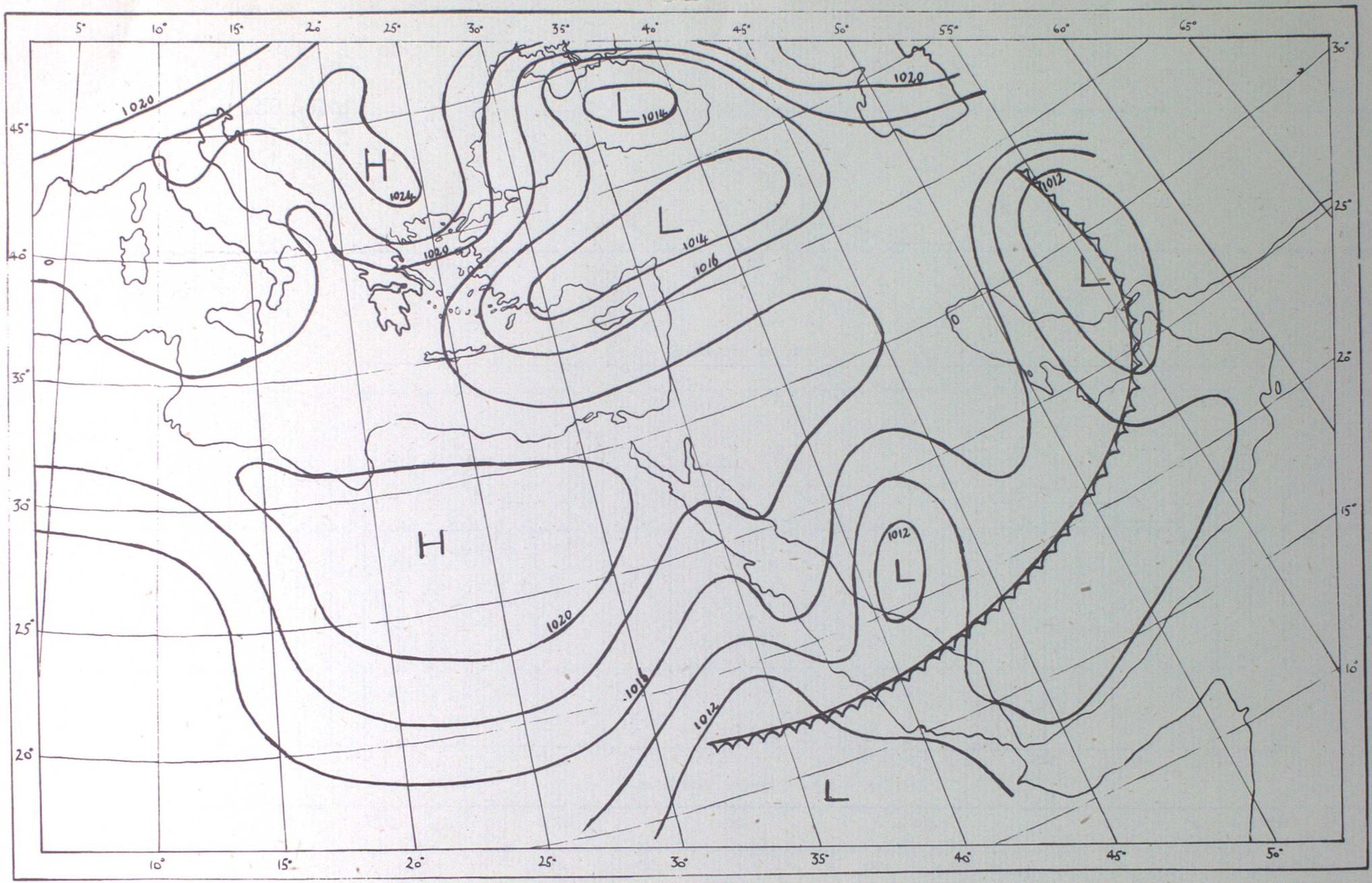


Fig. 10. Surface Synoptic Chart. 0300 G.M.T. February 25, 1954.

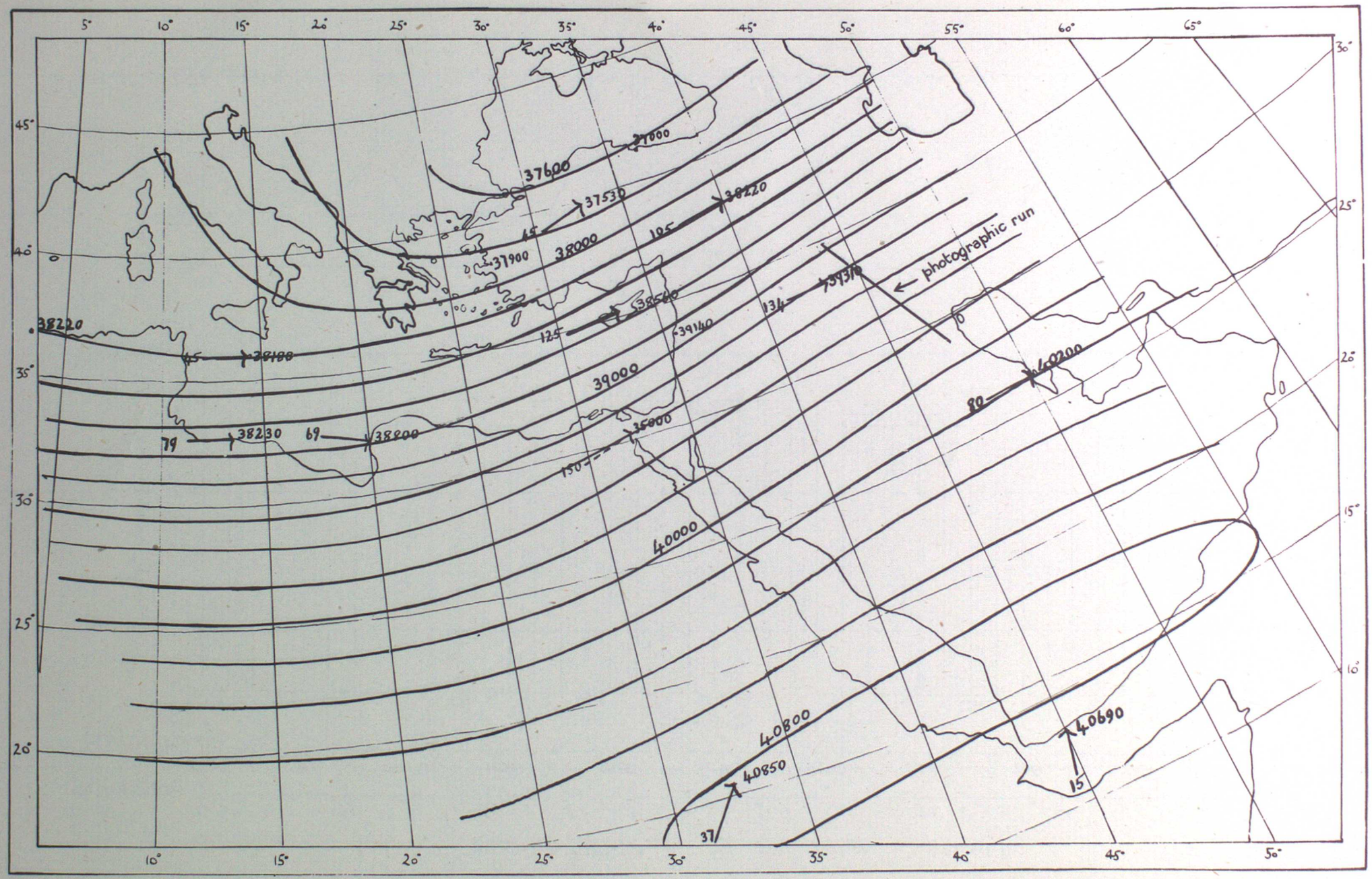


Fig. 11. 200mb. chart 0300 G.M.T. February 25, 1954. 200mb. heights (feet) and radar winds (knots) 100 ⟶ 38,500
Pilot balloon wind (knots) at height indicated 60 - - → 35,000.

M.R.P. 932

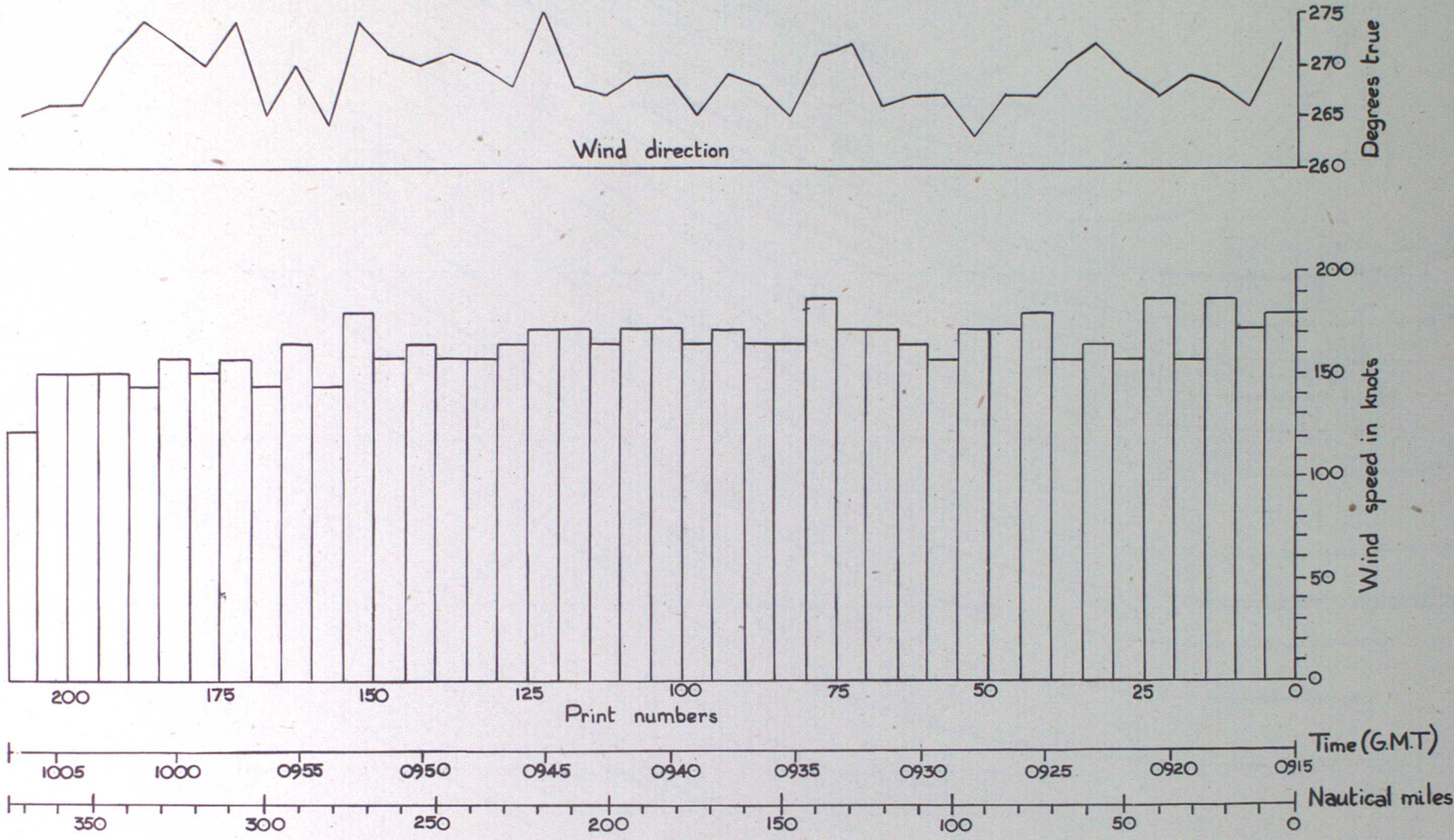


FIG. 12 Windy Run IX February 25, 1954.

M.R.P. 932

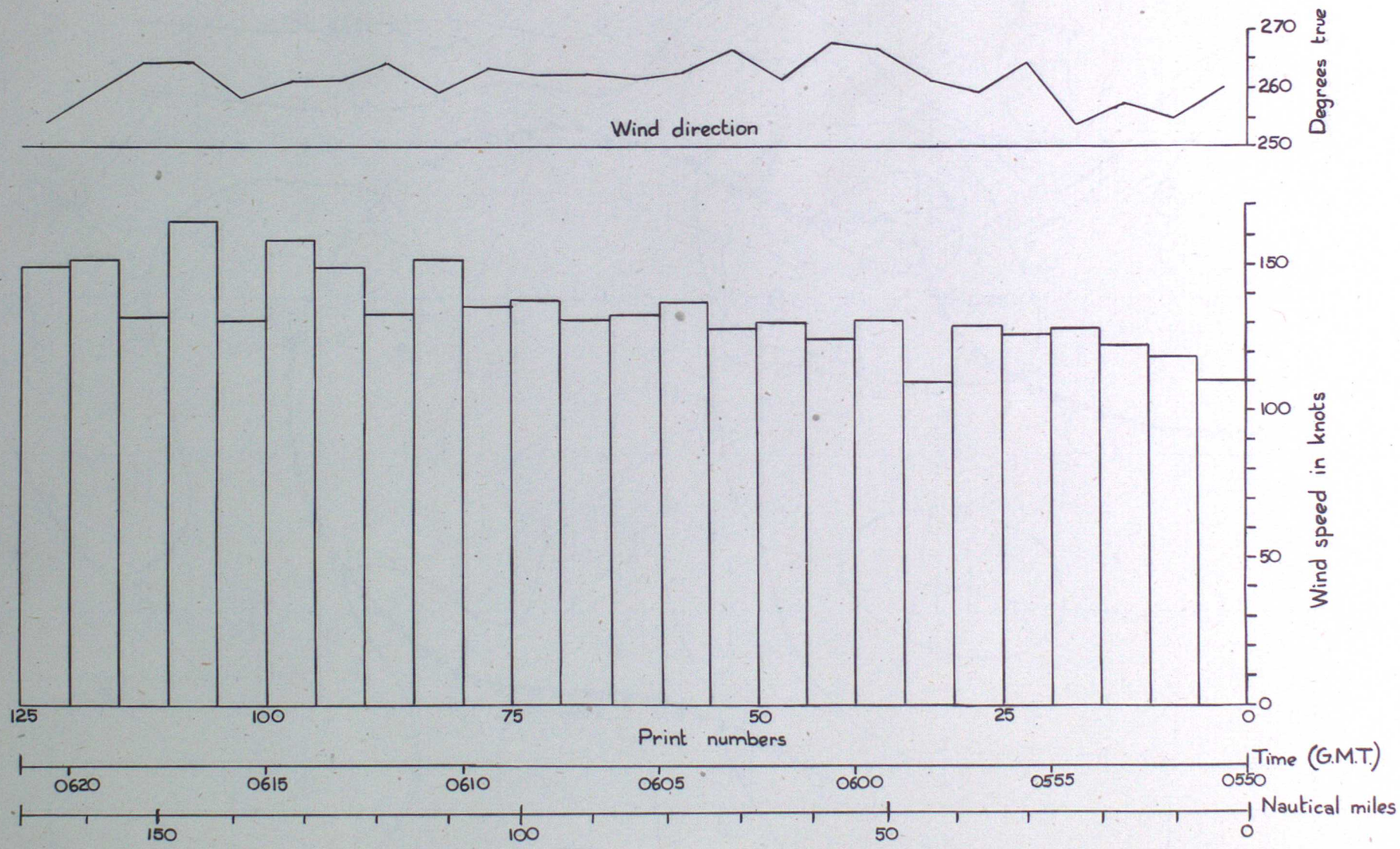


FIG. 13. Windy Run X February 26, 1954.

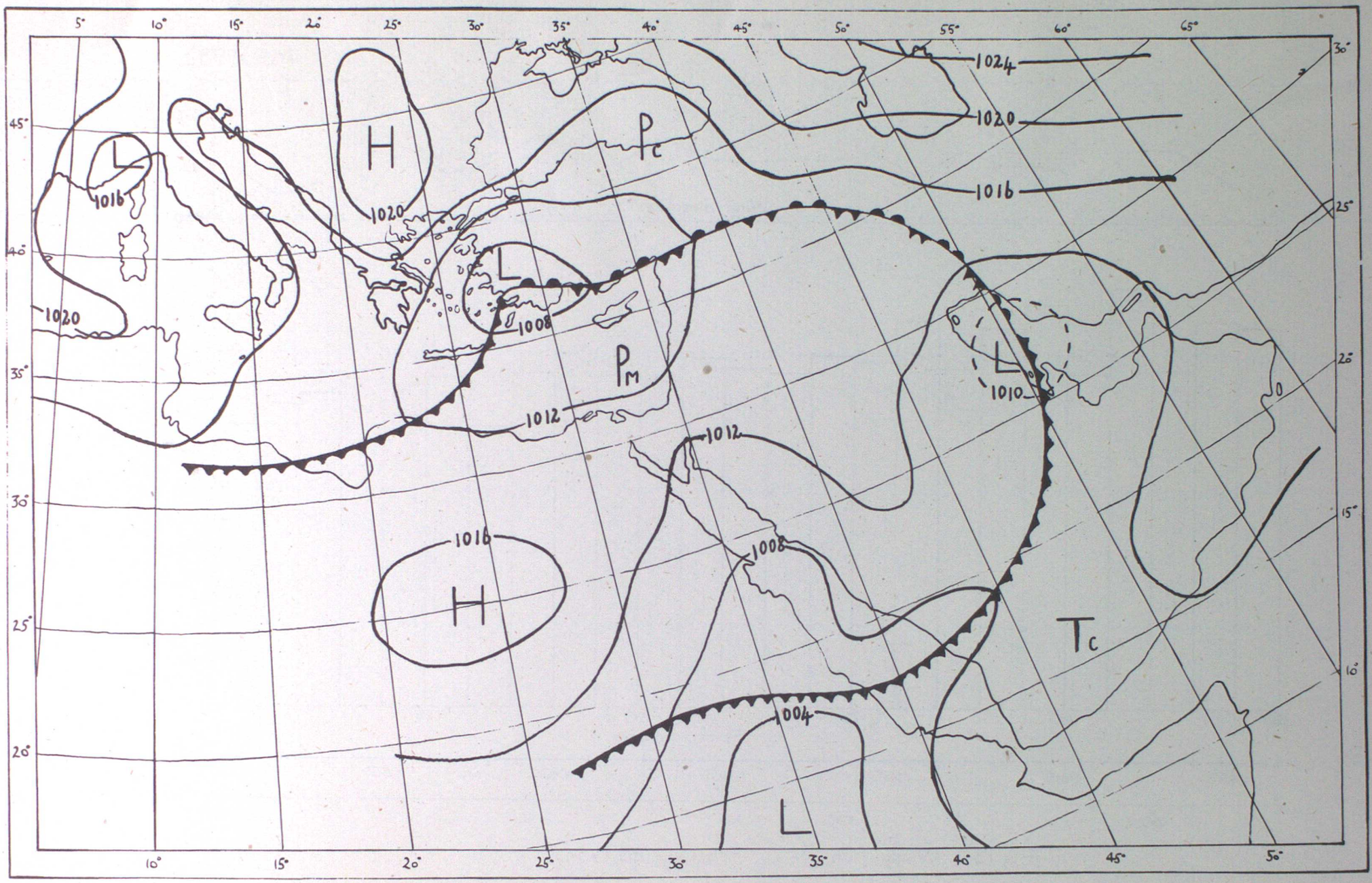


Fig. 14. Surface Synoptic chart. 0300 G.M.T. March 5, 1955.

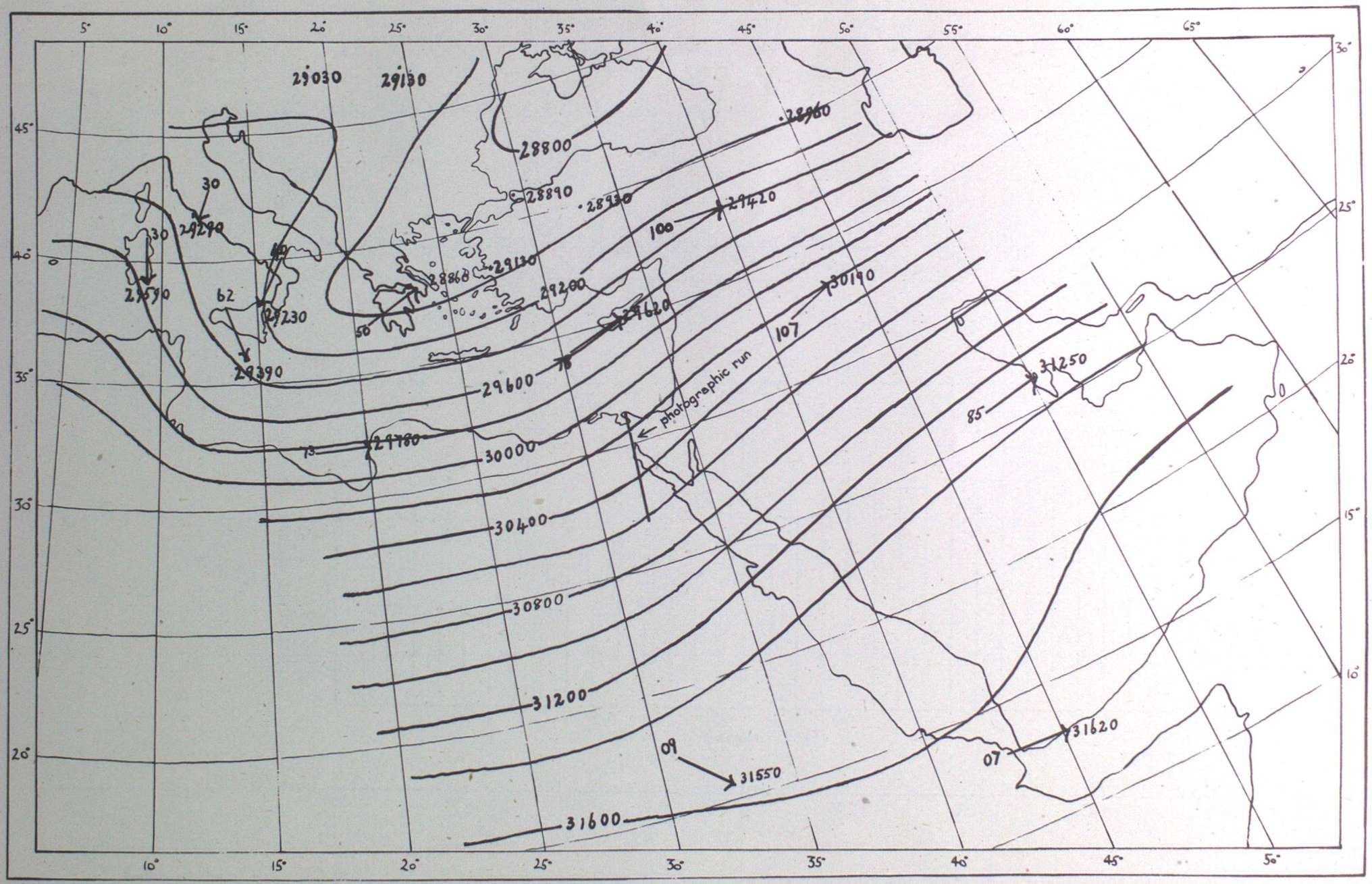


Fig. 15. 300mb. chart. 0300 G.M.T. March 5, 1955. 300mb. heights (feet) and radar winds (knots) 100 ⟶ 30,000.

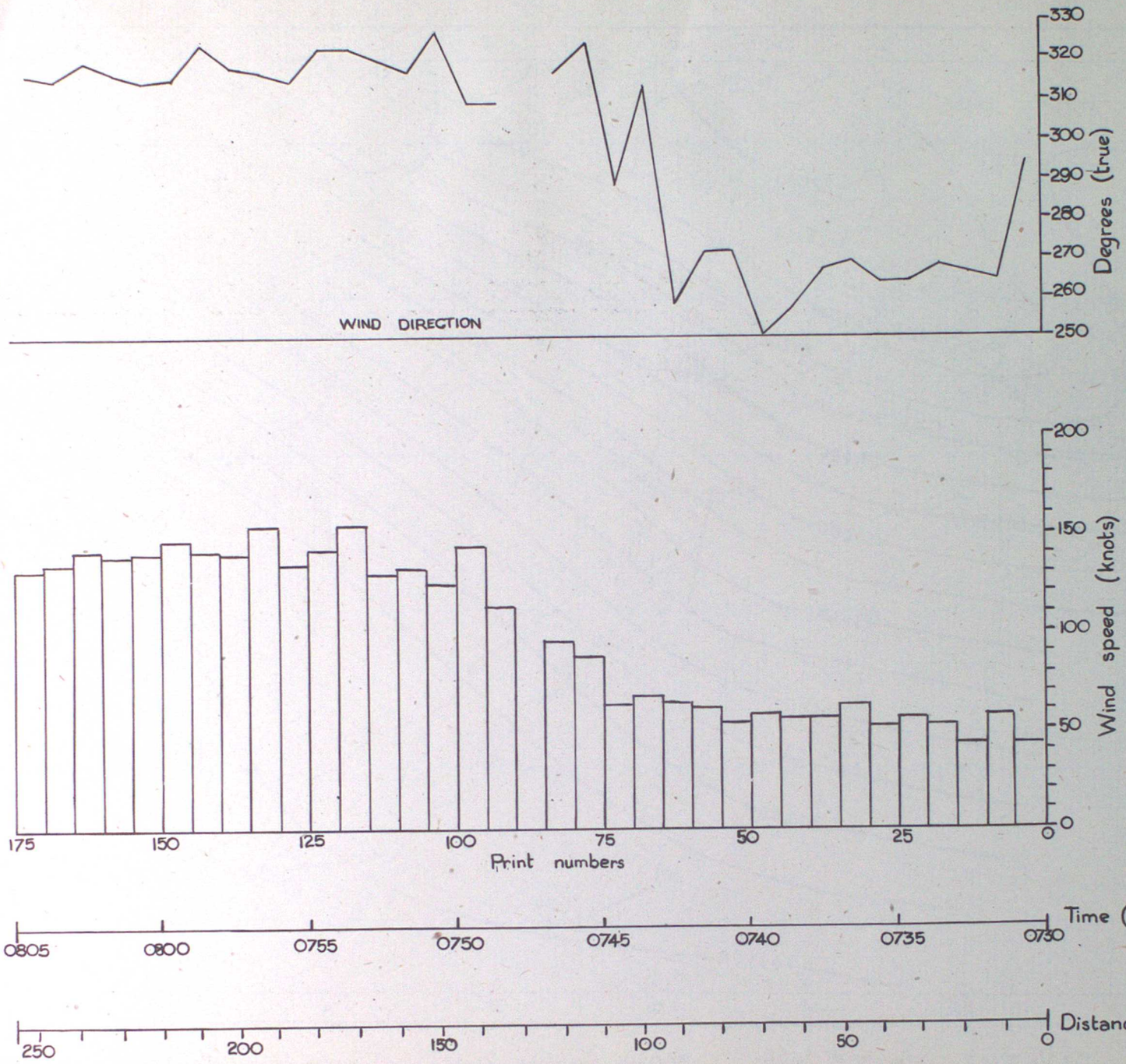


FIG. 16. Windy Run XI March 5, 1955.